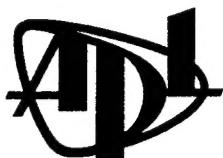


Calculating Apparent Forward Loss Using APL Bottom Bistatic Scattering Cross Sections

by Kevin Williams

Technical Memorandum
APL-UW TM 1-98
September 1998



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ABSTRACT

Calculations are carried out to examine the approximation of treating forward scattering from sediments as a forward reflection. The calculations use two different bistatic scattering models, both appropriate for acoustic frequencies between 10 and 100 kHz. The models are used to determine the intensity level of the energy forward scattered into a broad-beam receiver from a transmitter while the halfwidths of the transmitter's horizontal and vertical beams are varied from 2° to 30°. This intensity is compared to the level that is predicted if the sediment is assumed to be perfectly flat so that a reflection process can be used. Four different sediment types are examined: silt, sand, cobble, and rock. For a silt sediment it is found that, for single scattering and the pulse widths examined, a transmitter with equal vertical and horizontal halfwidths greater than 4° would have a peak intensity within 2 dB of that calculated for a reflection. To be within 2 dB of the reflection calculated for a rock sediment, the transmitter halfwidths would have to be greater than 11°. The results for sand and cobble are within these two extremes. Smaller halfwidths lead to correspondingly larger errors when using the reflection approximation.

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1. INTRODUCTION

The results discussed in this memorandum are appropriate for acoustic frequencies of 10 to 100 kHz. At acoustics frequencies above several kilohertz, the interaction of sound with ocean sediments is primarily a scattering process. However, most of the Navy simulation codes at present cannot incorporate this physics into their calculations. The codes treat the forward propagation of sound in terms of a "bounce" off the bottom that implicitly assumes that the bottom is flat and that the bounce is a reflection process. In many cases this approximation is quite adequate. This memorandum discusses the nature and magnitude of the errors introduced in this approximation so that simulators can examine them in the context of their individual efforts.

Unfortunately, it is hard to make general statements as to the errors introduced by assuming reflection instead of scattering. This is because the errors depend in a fundamental way on the particular geometries, sensor characteristics, and waveforms involved. This being the case, the goal here is to examine the problem of sound propagation from a source to a receiver that includes one interaction with the bottom, with that interaction being calculated via two models of the bistatic scattering process.

The two models are described in general terms in Section 2. Details of the models are given in the references in that section. The first model described is for "soft" sediments (defined in Section 2). That model has been tested in field experiments with success. The second model is relatively new and at present untested experimentally. This model was developed to fulfill a need in the simulation community to handle "harder," "rougher" sediments (sediments that do not fulfill the soft sediment criteria).

In Section 3, the forward loss issue is examined in the context of a particular geometry. The horizontal and vertical beamwidths of the receiver are held at a constant value, and an "apparent" forward loss is calculated, using the bistatic models described in Section 2, for different transmitter beamwidths. Several types of sediments are examined. Section 4 discusses the results in terms of their implications regarding treating the interaction of sound with the bottom as a reflection process.

2. BISTATIC MODELS

2.1 Soft Sediments

The model used to calculate bistatic scattering from soft sediments (referred to in the following as the 9407 model) is detailed in Section IV.D of the Applied Physics Laboratory Models Document.¹ The term “soft” indicates both a low shear wave speed and an interface roughness whose parameters imply that the Kirchhoff and perturbation approximations are valid (see Ref. 1, page IV-31). The results of the 9407 model agree with experimental measurements in both a sand² and a sand-silt-clay³ environment.

The 9407 model treats scattering due to both roughness of the seabed and inhomogeneities in the sediment volume. The total cross section is assumed to be a sum of two terms, the roughness-scattering cross section and the volume-scattering cross section. A major assumption in the model is that the sediment can be treated as a lossy fluid. It is further assumed that there are no gradients in sediment properties, apart from the random fluctuations responsible for volume scattering. Thus the sediment can be characterized by three parameters: mass density, sound speed, and acoustic absorption coefficient. The seabed relief is assumed to be an isotropic, two-dimensional Gaussian random process completely determined by a spectral density that follows a simple power law in wavenumber. This adds two more parameters to the model: the exponent of the power law and a parameter that sets the overall spectral level. The volume scattering strength is also assumed to follow a power-law form, which adds the final three parameters to the model: the exponent of the power law, a parameter that sets the overall spectral level, and a parameter that relates density and compressibility fluctuations. Volume scattering is assumed to be weak in the sense that the scattered field is much smaller in magnitude than the incident field (defined as the field that would exist in the sediment in the absence of volume scattering).

2.2 Hard Sediments

The model described in Ref. 4 (referred to hereafter as the hard sediment model) is a generalization of the 9407 model applicable to both soft, smooth sediments and harder, rougher sediments. In particular, it treats scattering as being due to both roughness of the seabed and inhomogeneities in the sediment volume. Also, the total cross section is still assumed to be a

sum of two terms, one proportional to the roughness-scattering cross section and the other to the volume-scattering cross section.

There are several significant differences in the assumptions and methods used in the 9407 model and in the model for harder sediments. The latter treats the sediment as a viscoelastic solid instead of a fluid. Thus the sediment is characterized by five parameters: mass density, compressional wave sound speed, a compressional wave loss parameter, shear wave sound speed, and a shear wave loss parameter.

The seabed relief is still assumed to be an isotropic, two-dimensional Gaussian random process completely determined by a spectral density that follows a simple power law in wave-number; however, the roughness cross section is calculated using the small slope approximation. This is because the values of the roughness power law exponent and strength parameter are such that Kirchhoff theory and first-order perturbation theory (assumed in the 9407 model) are not valid. (As an aside, the small slope approximation actually turns out to be a better approximation for the softer sediments also, in that there is no need to interpolate between Kirchhoff and perturbation theory when going from forward scattering to backscattering. Thus it is anticipated that the small slope approximation will eventually be used in calculating the surface cross section for all sediment types.)

In the viscoelastic model, volume inhomogeneity spectra are assumed to follow a power law behavior at high wavenumbers. An algebraic cutoff at low wavenumbers is included to prevent unphysical divergences in the scattering cross sections near forward scattering. Furthermore, the inhomogeneities can be correlated, implying that cross spectra that account for these correlations can be important. Finally, each type of inhomogeneity can cause four different types of wave conversion: compressional to compressional, compressional to shear, shear to compressional, and shear to shear.

As used here, the hard sediment model has 11 input parameters in addition to the speed of sound in the water above the sediment. Five give the mean sediment properties: mass density, compressional wave sound speed, a compressional wave loss parameter, shear wave sound speed, and a shear wave loss parameter. Two quantify the sediment roughness: the exponent of the power law and the overall spectral level. The final four account for volume in-

homogeneities: the exponent of the power law, the spectral level, the ratio of compressibility to density fluctuations, and the low-frequency algebraic cutoff. In obtaining the parameter set used to define volume inhomogeneities, it has been assumed that compressibility and density are inversely correlated and thus there are no sound speed fluctuations. This is consistent with physics, since density and compressibility tend to be inversely correlated, and with the calculations carried out for the soft sediments, in which the density and compressibility are also assumed to be inversely correlated.

3. CALCULATION OF FORWARD LOSS

The link between bistatic scattering and forward loss is the model for the intensity of scattering from the seabed as a function of time. The energy received at any time depends not only on the bistatic scattering cross section of the seabed but also on the geometry and the type of pulses used. The intensity model accounts for all these factors via an integration over the area of the seabed that is scattering energy into the receiver. The result of this integration is a pulse in the time domain. Most Navy simulations approximate this pulse as a reflection, in which case the peak level of the received signal is not affected by the transmitter beamwidths. Here, the peak of that pulse is calculated using bistatic scattering models and determined as a function of the vertical and horizontal beamwidths of the transmitter. The reduction of the peak as the beamwidths are reduced is determined and plotted as an "apparent" forward loss. The "apparent" loss is the loss in addition to that calculated using a specular reflection coefficient. Thus an apparent loss of 0 dB implies that approximating the scattering as a reflection does not lead to an error in determining the level of the received signal.

The expression given below² is for the scattered intensity $I(t)$ of a short-duration, or "impulse," pulse. This expression was convolved with the transmitted signal (intensity vs time) to predict the absolute levels and temporal structure of the scattered pulse.

$$I(t) = I_0 \iint \left[\frac{(\sigma b_x b_r)}{(D_1 D_2)^2} 10^{-\frac{\alpha_w (D_1 + D_2)}{10}} \right] dx dy . \quad (1)$$

Here, σ is the sum of the surface- and volume-scattering cross sections predicted by the 9407 model or the hard sediment model, α_w is the attenuation of sound in water for the frequency of interest in decibels per unit length, b_x and b_r are the beam patterns of the transmitter and

receiver, respectively, and D_1 and D_2 are the distances shown in Figure 1. The source is assumed to emit a rectangular pulse of infinitesimal length dt that has intensity I_0 at a range of 1 m.

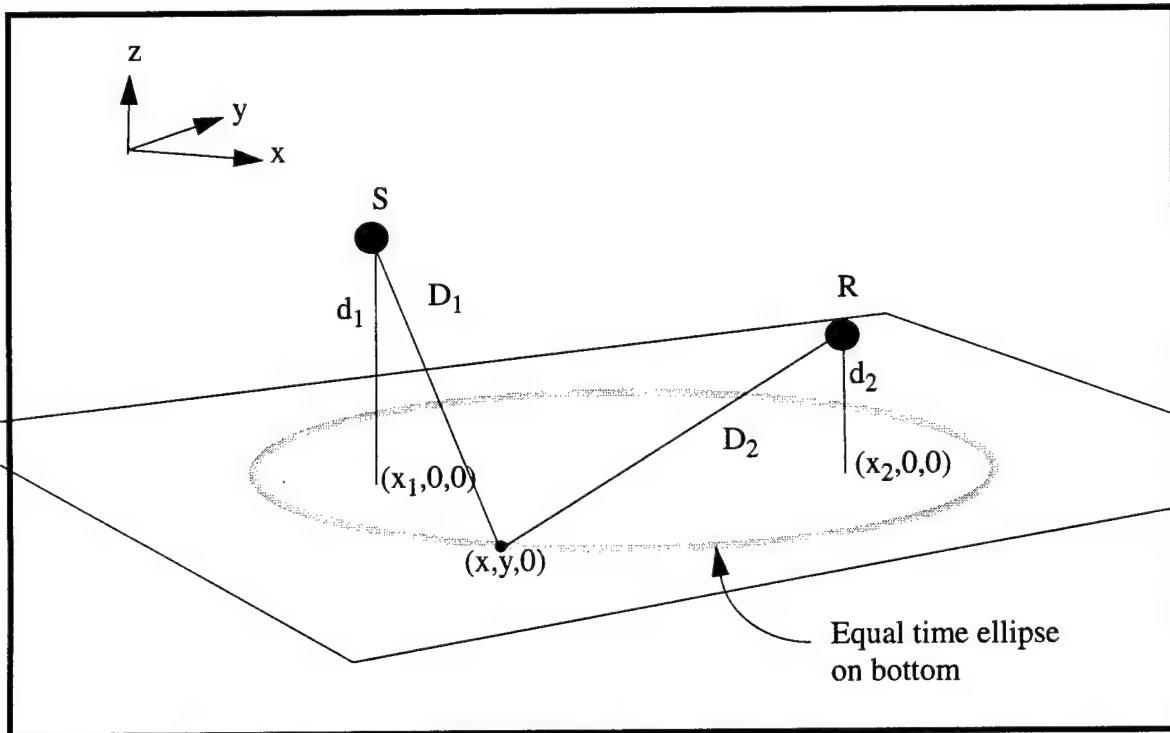


Figure 1. Diagram defining geometrical parameters of Eq. 1.

The integrations in Eq. 1 are over the infinitesimal area lying between two ellipses (one is shown schematically in Figure 1), which have associated travel times from transmitter to seabed to receiver of t and $(t + dt)$. Therefore the limits on the x and y integrations in Eq. 1 are actually functions of time.²

For the results described in this section, Gaussian beampatterns were assumed for the source and receiver, and the centers of all beams were aimed at the specular reflection point. The horizontal and vertical (\exp^{-1}) halfwidths of the receiver beam were set to 30° . The transmitted pulses were 10 ms in duration with a carrier frequency of 35 kHz. The source was placed such that $x_1 = 0$, $d_1 = 50$ m, $x_2 = 400$ m, and $d_2 = 50$ m (see Figure 1).

In practice, the code that calculates the apparent reflection loss for soft sediments first calculates the peak received intensity of a pulse scattered off a particular sediment when both the transmitter and receivers beams have horizontal and vertical (\exp^{-1}) halfwidths of 30° . The results are within 1 dB of those calculated for the same sediments when using a specular reflection coefficient (the 1 dB difference arises from a combination of the finite patch sizes used in approximating the integral in Eq. 1 and the finite region of the bottom over which the approximation is evaluated). The apparent losses plotted in Figures 2 and 3 are the differences between the peak intensity for the 30° halfwidth and the intensities calculated as the halfwidths of the transmitter beam are reduced.

In calculating the apparent loss for rough, hard sediments, the reflection coefficient for a flat surface with the same material parameters as the sediment was calculated and then used to determine a received peak intensity. The difference between this peak intensity and that calculated for different transmitter beampatterns is plotted in Figures 4 and 5. This method was chosen because of a concern that even for the broadest beampatterns examined there might already be a substantial apparent loss.

Note that the narrowest transmitter halfwidths examined for all the sediment types are 2° . Figures 2 through 5 show apparent loss contours as functions of the transmitting beam's horizontal and vertical halfwidths. The figure captions give the model (9407 or hard sediment) used in calculating the contours. The sediment parameters used in the calculations are given as part of the figure. The next section discusses the figures in terms of their implications for treating the interaction of sound with the bottom as a reflection process.

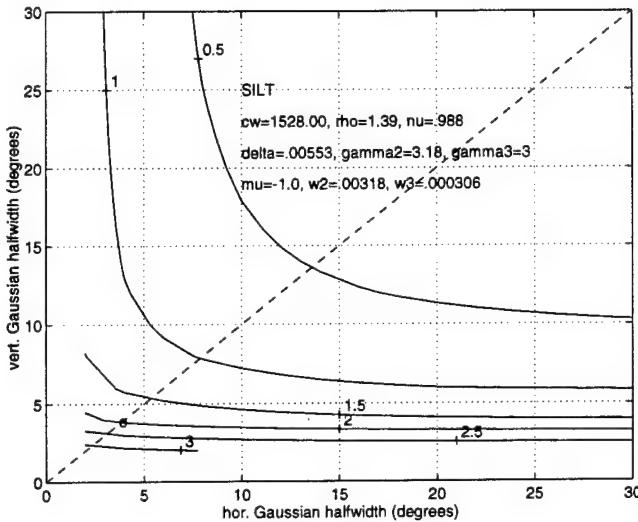


Figure 2. Contour lines of apparent reflection loss (solid curves) as a function of transmitter vertical and horizontal halfwidths for a silt sediment with the parameters given in the figure. The calculation used the 9407 model. The dashed line indicates equal horizontal and vertical beamwidths. The circle indicates the halfwidth at which a transmitter with equal vertical and horizontal beams would give an apparent loss of 2 dB. (See text for definition of apparent reflection loss.)

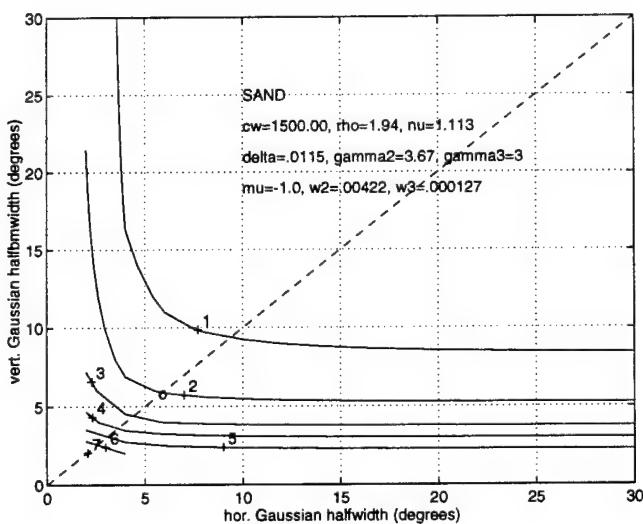


Figure 3. Contour lines of apparent reflection loss (solid curves) as a function of transmitter vertical and horizontal halfwidths for a sand sediment with the parameters given in the figure. The calculation used the 9407 model. The dashed line indicates equal horizontal and vertical beamwidths. The circle indicates the halfwidth at which a transmitter with equal vertical and horizontal beams would give an apparent loss of 2 dB.

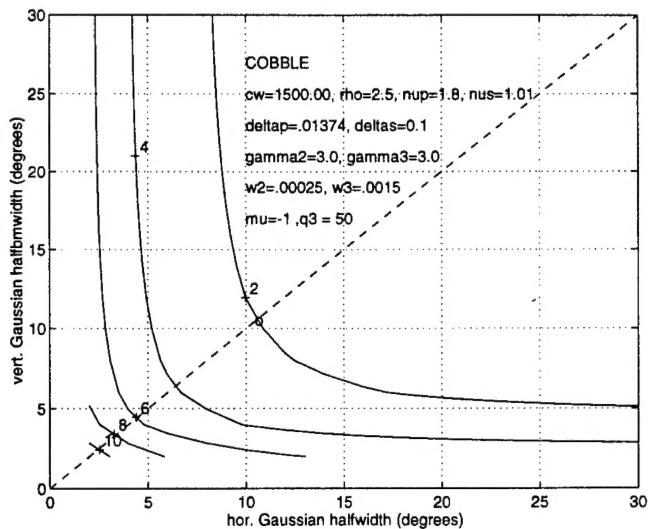


Figure 4. Contour lines of apparent reflection loss (solid curves) as a function of transmitter vertical and horizontal halfwidths for a cobble sediment with the parameters given in the figure. The calculation used the hard sediment model. The dashed line indicates equal horizontal and vertical beamwidths. The circle indicates the halfwidth at which a transmitter with equal vertical and horizontal beams would give an apparent loss of 2 dB.

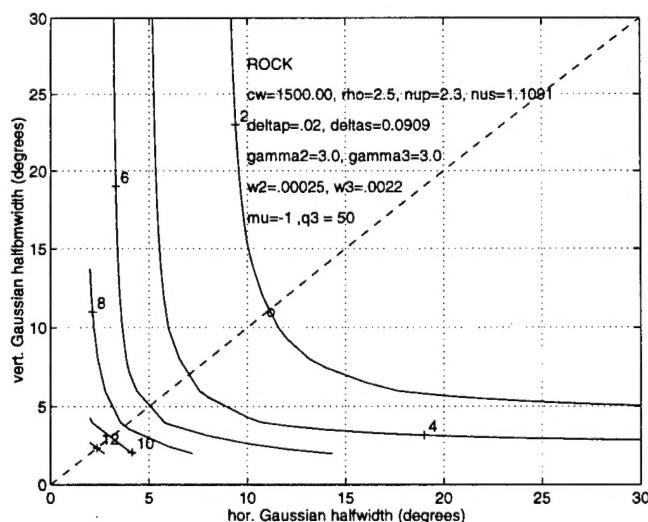


Figure 5. Contour lines of apparent reflection loss (solid curves) as a function of transmitter vertical and horizontal halfwidths for a rock sediment with the parameters given in the figure. The calculation used the hard sediment model. The dashed line indicates equal horizontal and vertical beamwidths. The circle indicates the halfwidth at which a transmitter with equal vertical and horizontal beams would give an apparent loss of 2 dB.

4. DISCUSSION

It is important to emphasize again that the results shown in Figures 2–5 are good only for the particular geometry chosen. Other cases of single scattering can be examined by using Eq. 1 and the models in Ref. 1 or 4 for the bistatic cross section. Multibounce cases need to be handled by simulating the bistatic scattering from each interaction with a rough interface. The apparent losses calculated for single interactions cannot necessarily be added.

Nonetheless, the results certainly indicate that as sediment becomes harder and rougher the much broader bistatic scattering cross section⁴ leads to larger apparent losses given the same beamwidths or, equivalently, that much larger beamwidths are needed if the apparent loss is to be kept below a designated value. Figure 2, for instance, indicates that a transmitter with equal vertical and horizontal halfwidths greater than 4° would have an apparent loss of 2 dB or less for a silt bottom. To obtain an apparent loss of 2 dB or less for a rock sediment, the transmitter halfwidths would have to be greater than 11°.

Further examination of the figures also indicates that for soft sediments reducing the vertical beamwidth has a larger effect than reducing the horizontal beamwidth. For sand (Figure 3) a horizontal halfwidth of 10° and a vertical halfwidth of about 6° or a vertical halfwidth of 10° and a horizontal halfwidth of 3° both give an apparent loss of 2 dB. The opposite is true for harder sediments; for rock (Figure 5), a horizontal halfwidth of 15° and a vertical halfwidth of about 7° or a vertical halfwidth of 15° and a horizontal halfwidth of 10° both give an apparent loss of 2 dB. This is because for hard sediments the contribution from volume scattering is much more significant, and volume scattering contributes significantly to out-of-plane scattering. Out-of-plane scattering is sensitive to reduction of the horizontal beamwidth.

It is apparent that in shallow water where several bounces off a hard sediment occur, the use of a reflection approximation introduces large error even if the transducers have large beamwidths. In these cases, it would seem that bistatic scattering effects need to be accounted for in simulators if quantitative predictions are to be made.

We note again that the hard sediment model used in the calculations for cobble and rock has not been tested in field experiments. However, the 9407 model used for the soft sediments compared well with data, and the hard sediment model actually reproduces, with minor differences, the 9407 model when used on soft sediments, giving some confidence in the model. The first experimental test of the hard sediment model is scheduled for May 1999.

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